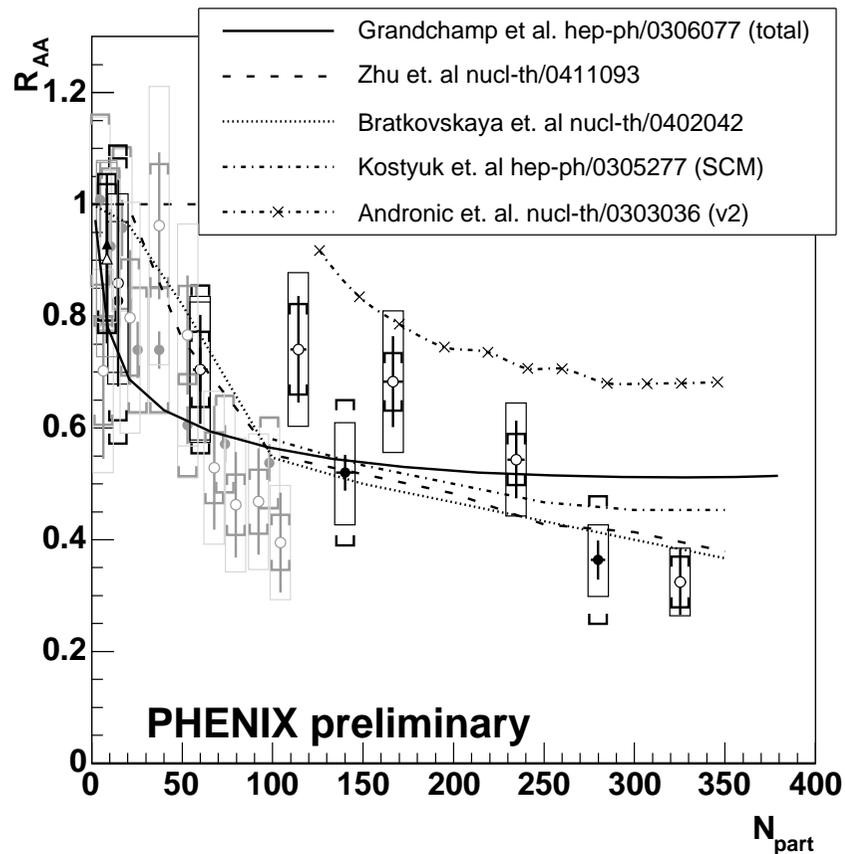


CHARMONIUM IN MEDIUM AND AT RHIC

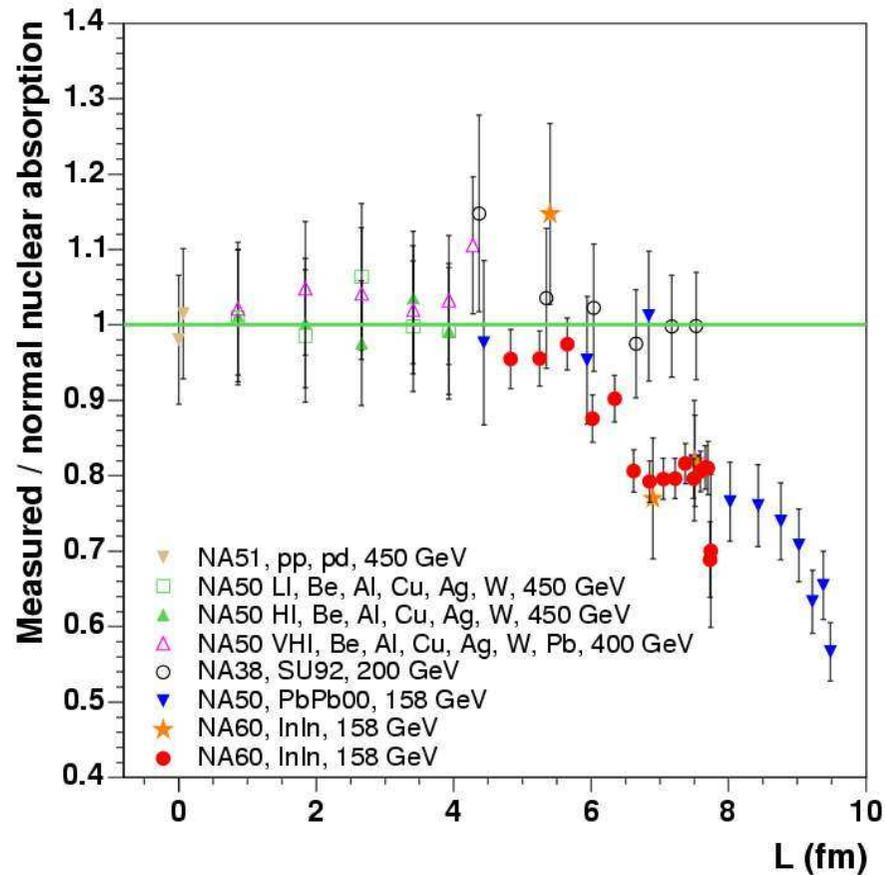
David Blaschke (JINR Dubna & GSI Darmstadt)



- New data: SPS-NA60, RHIC-PHENIX
 - Full diss./recombination kinetics
- Lattice QCD: Hadrons above T_c
- Mott-Effect and quark rearrangement
- Example: J/psi dissociation kinetics
 - Quantum kinetics in a resonance gas
 - In-medium cross section
 - Dissociation rate
- Summary / Outlook

CHARMONIUM IN MEDIUM AND AT RHIC

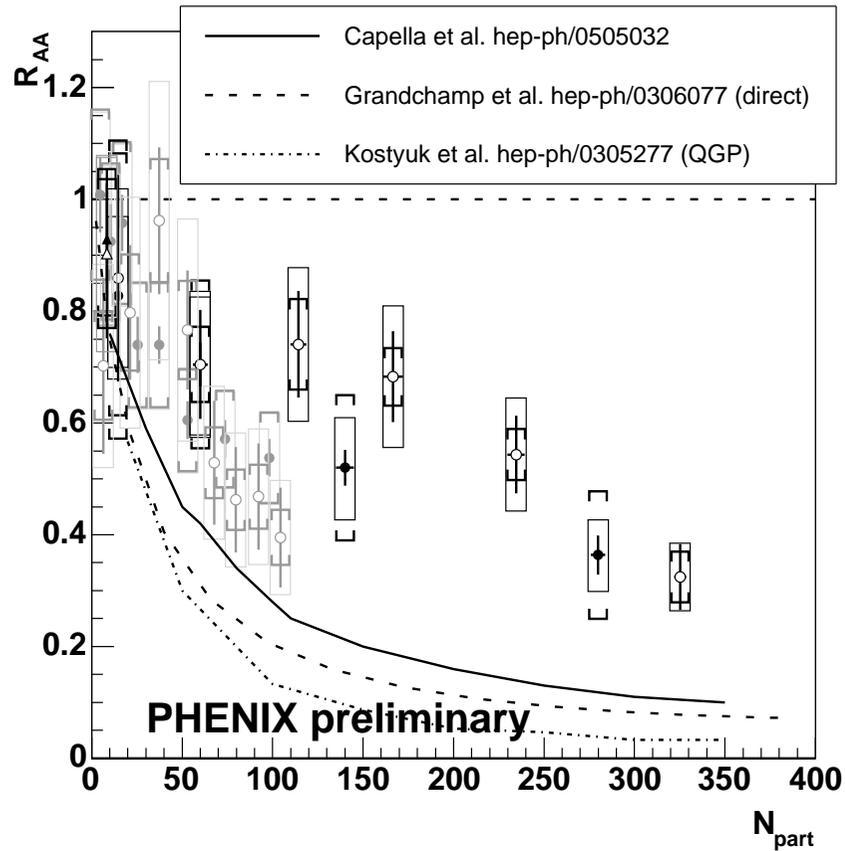
David Blaschke (JINR Dubna & GSI Darmstadt)



- New data from SPS-NA60
 - Failure of L: non-nucleonic absorption

CHARMONIUM IN MEDIUM AND AT RHIC

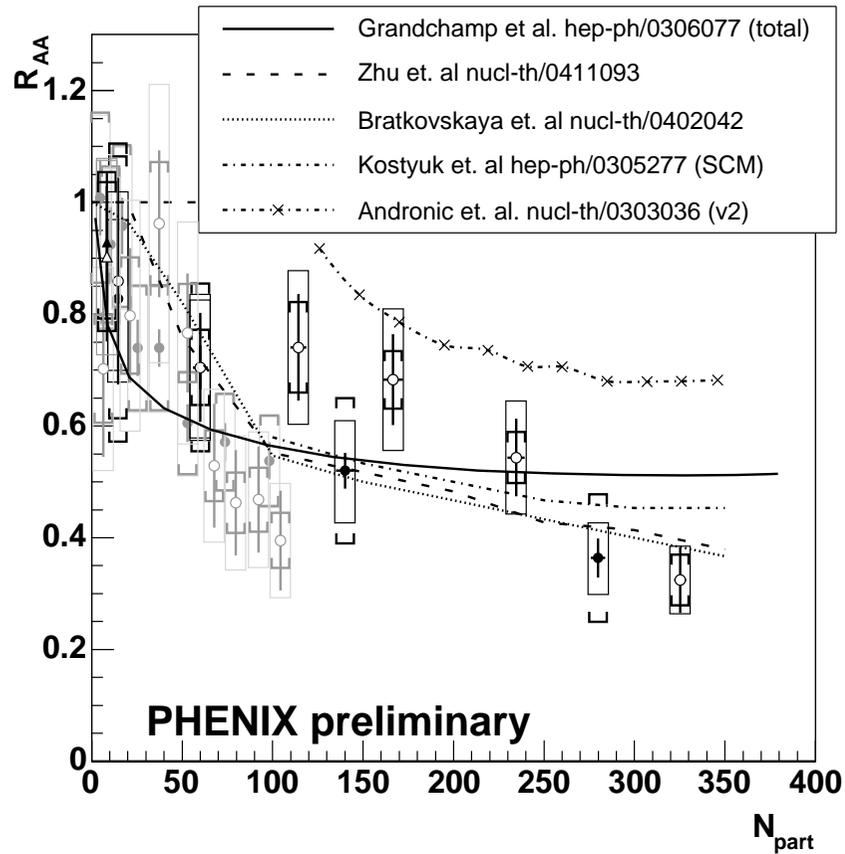
David Blaschke (JINR Dubna & GSI Darmstadt)



- New data from RHIC-PHENIX
- Failure of extrapolation SPS → RHIC

CHARMONIUM IN MEDIUM AND AT RHIC

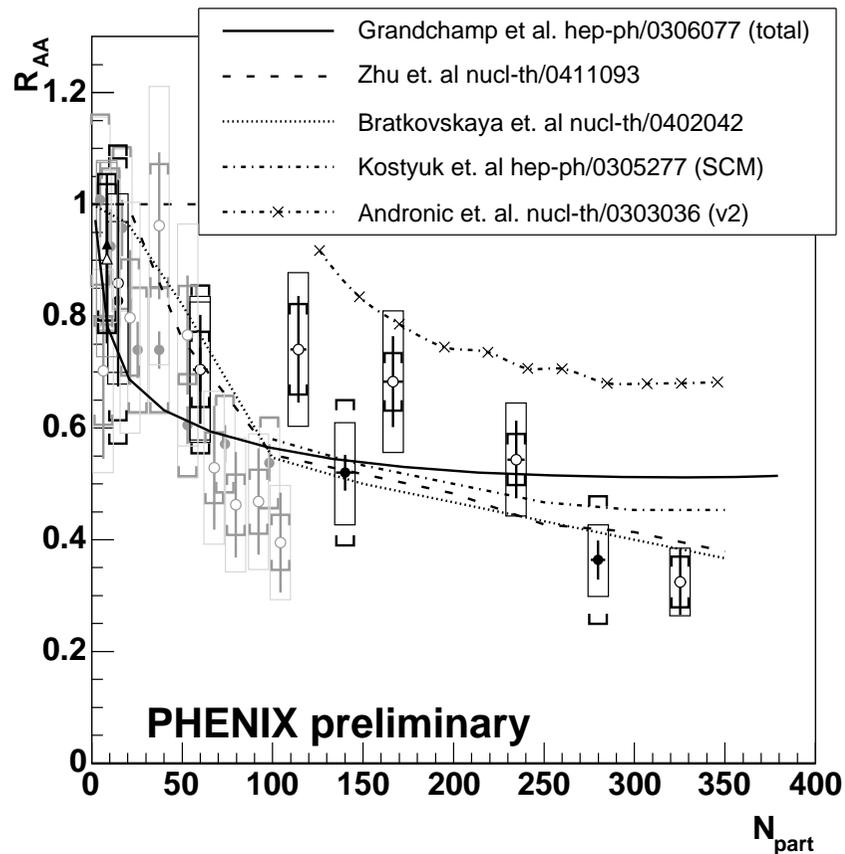
David Blaschke (JINR Dubna & GSI Darmstadt)



- New data from RHIC-PHENIX
- Full diss./recombination kinetics

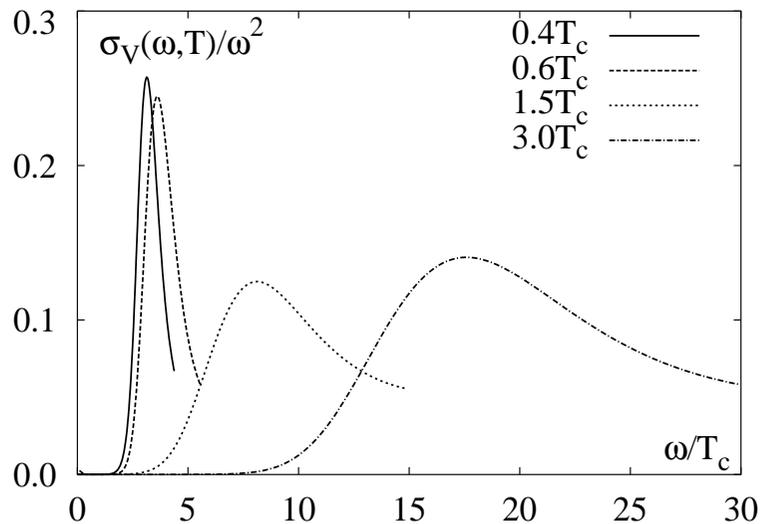
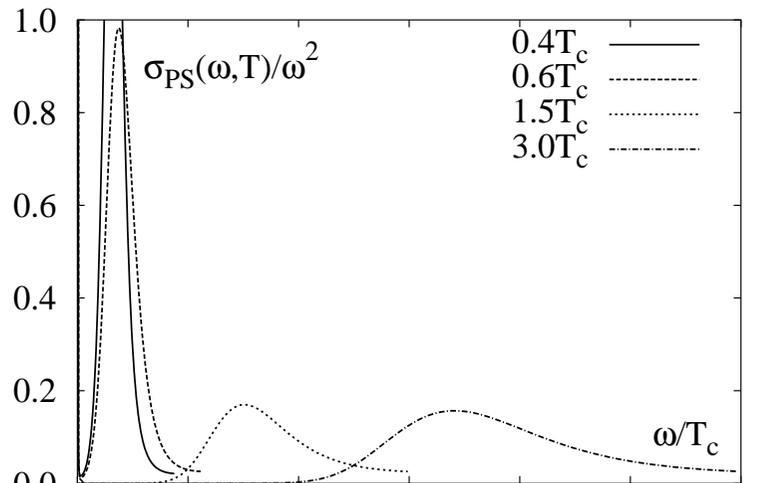
CHARMONIUM IN MEDIUM AND AT RHIC

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LATTICE QCD SPECTRAL DENSITIES



Hadron correlators $G_H \implies$ spectral functions σ_H

$$G_H(\tau, T) = \int_0^\infty d\omega \sigma_H(\omega, T) \frac{\cosh(\omega(\tau - T/2))}{\sinh(\omega/2T)}$$

Maximum entropy method

Karsch et al. PLB 530 (2002) 147

Result:

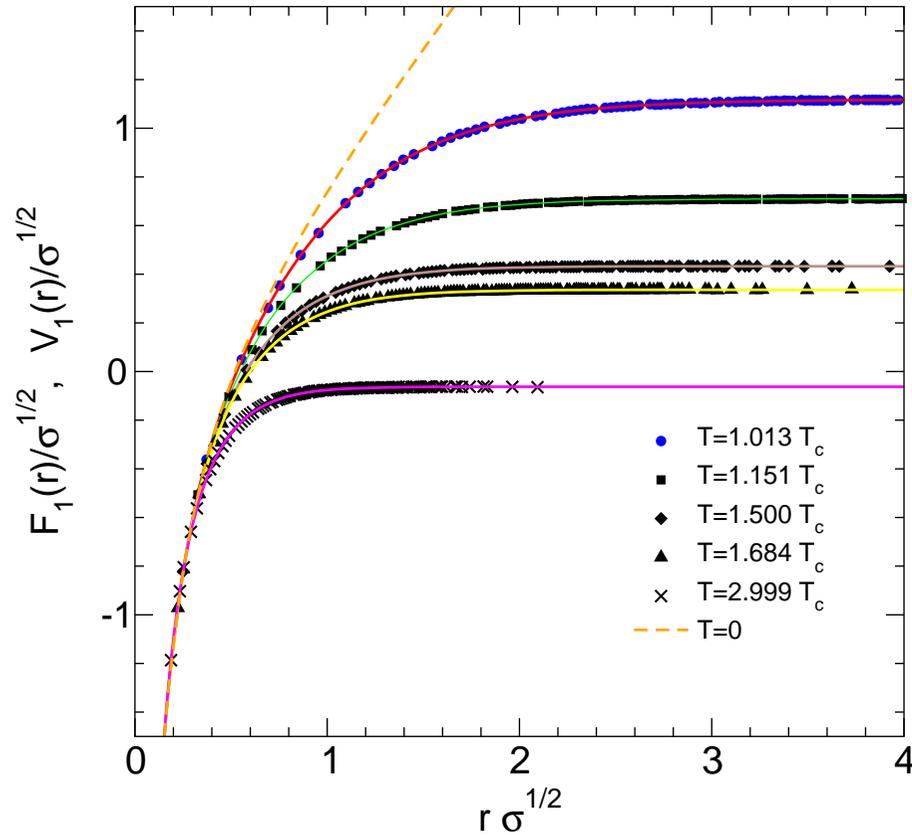
Correlations persist above T_c !

Karsch et al. NPA 715 (2003)

J/ψ and η_c survive up to $T \sim 1.6T_c$

Asakawa, Hatsuda; [hep-lat/0308034]

HEAVY QUARK POTENTIAL FROM LATTICE QCD



Blaschke, Kaczmarek, Laermann, Yudichev,
EPJC 43, 81 (2005); [hep-ph/0505053]

Color-singlet free energy F_1 in quenched QCD

$$\langle \text{Tr}[L(0)L^\dagger(r)] \rangle = \exp[-F_1(r)/T]$$

Long- and short- range parts

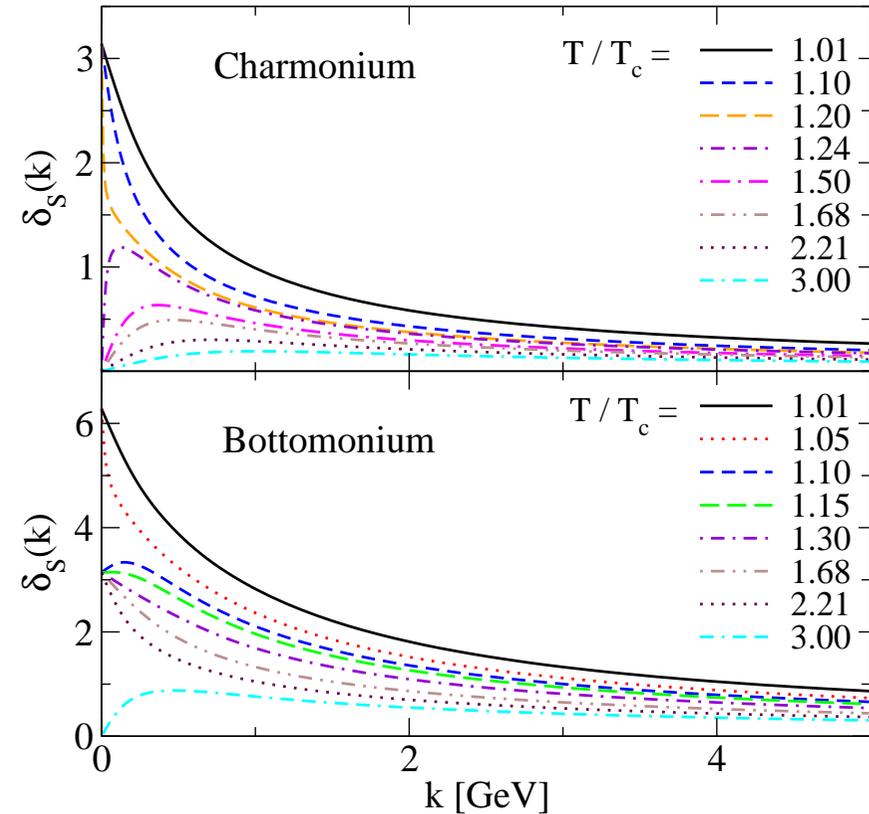
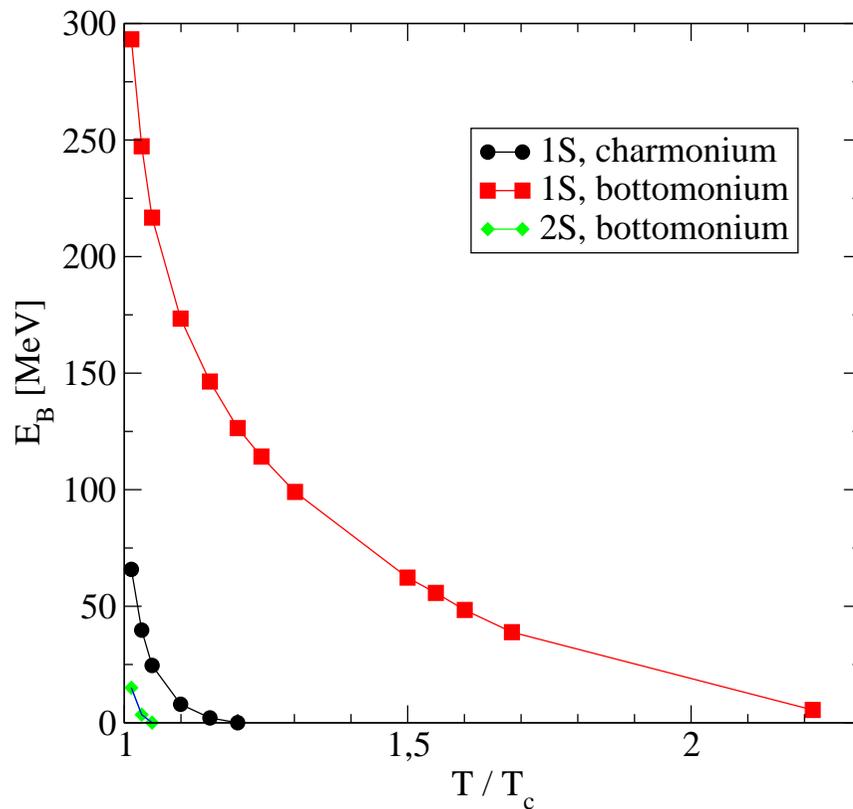
$$F_1(r, T) = F_{1, \text{long}}(r, T) + V_{1, \text{short}}(r) e^{-(\mu(T)r)^2}$$

$$F_{1, \text{long}}(r, T) = -\frac{q^2(T)}{2^{3/4}\Gamma(3/4)} \sqrt{\frac{r}{\mu(T)}} K_{1/4} \left[(\mu(T)r)^2 \right] + q^2(T) \frac{\Gamma(1/4)}{2^{3/2}\Gamma(3/4)\mu(T)},$$

$$V_{1, \text{short}}(r) = -\frac{4}{3} \frac{\alpha(r)}{r},$$

$$\alpha(r) = \frac{4\pi}{11} \left(\frac{1}{\ln(r^2/c^2)} - \frac{r^2}{r^2 - c^2} \right).$$

SCHROEDINGER EQN: BOUND & SCATTERING STATES

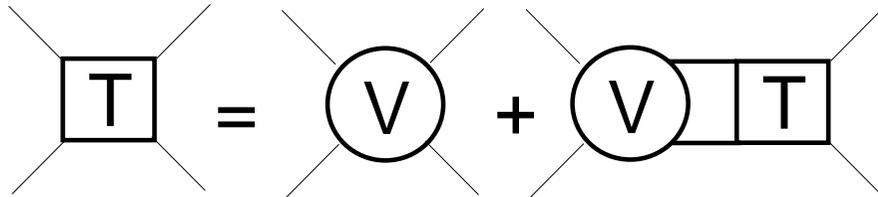


Blaschke, Kaczmarek, Laermann, Yudichev
EPJC 43, 81 (2005); [hep-ph/0505053]

Mott effect & Levinson theorem:
Resonances above T_{Mott}

PANIC @ SANTA FE, 24.-28.10.2005

T-MATRIX APPROACH TO QUARKONIA IN THE QGP



M. Mannarelli & R. Rapp, hep-ph/0505080

Open question: Which potential to use?

$$E_1 = F_1 - T \frac{dF_1}{dT}$$

$$V_1 = E_1(r, T) - E_1(\infty, T)$$

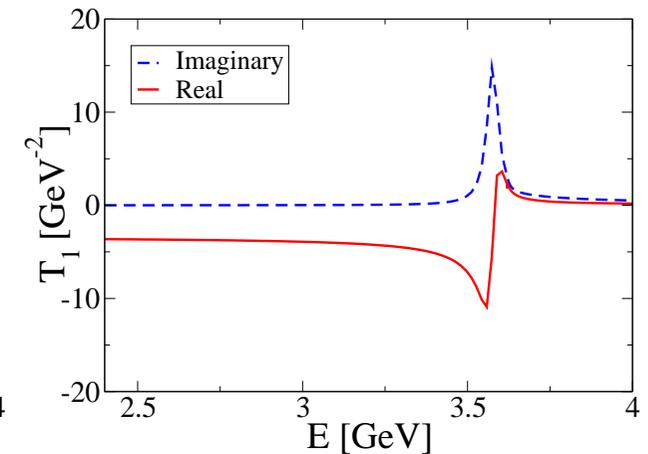
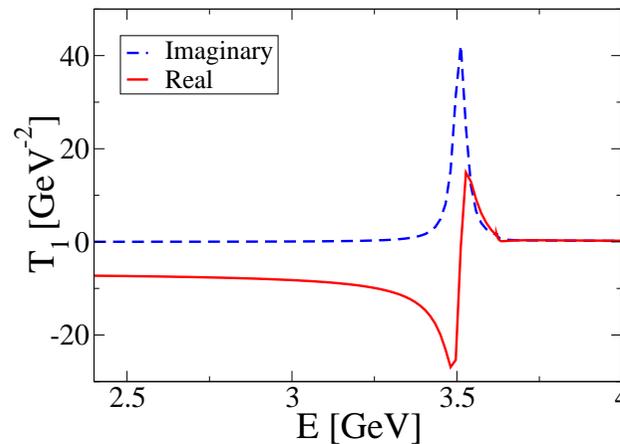
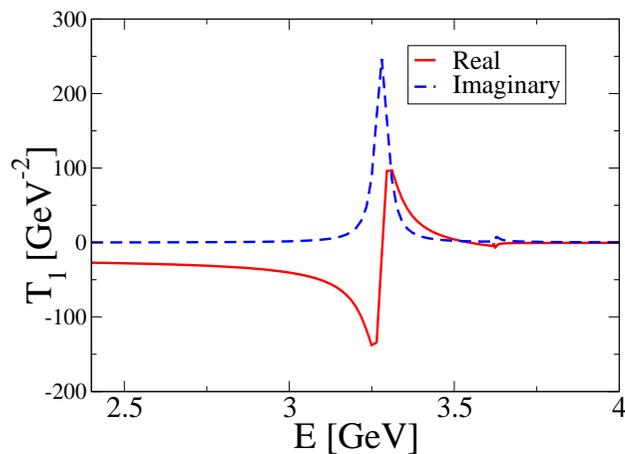
Result:

Good resonances well above T_c and T_{Mott}

$T = 1.2 T_c$

$T = 1.5 T_c$

$T = 2.0 T_c$

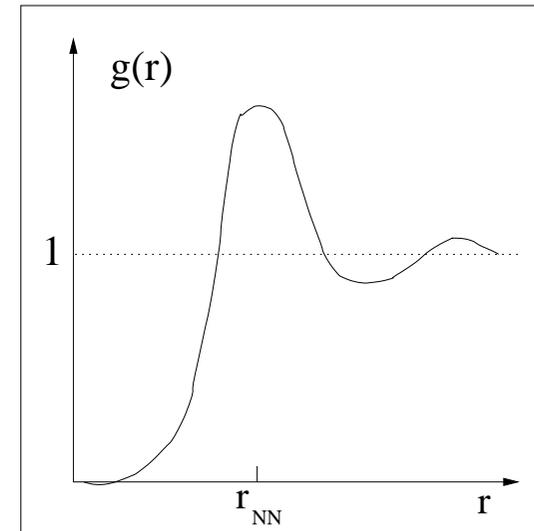
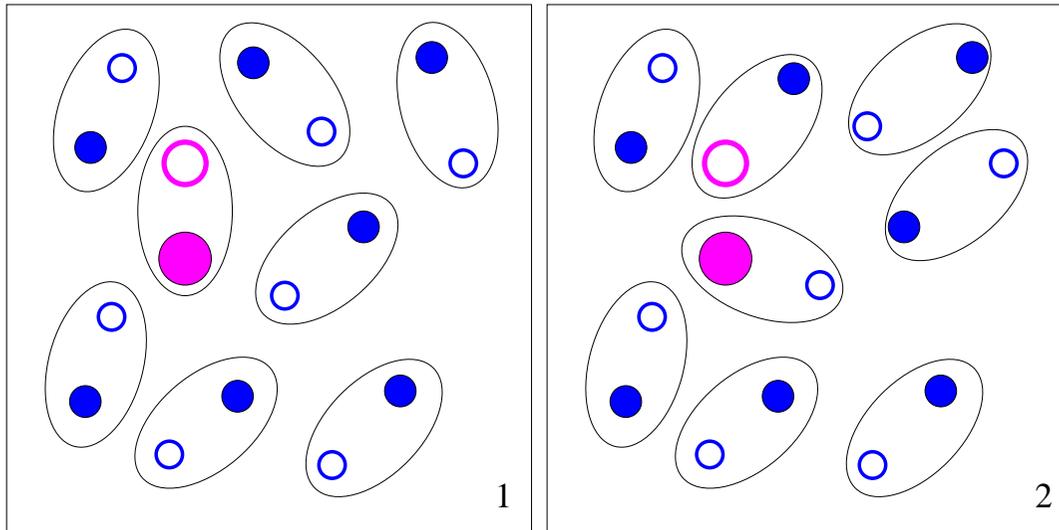


A SNAPSHOT OF THE SQGP

The Picture: String-flip (Rearrangement)



Pair correlation

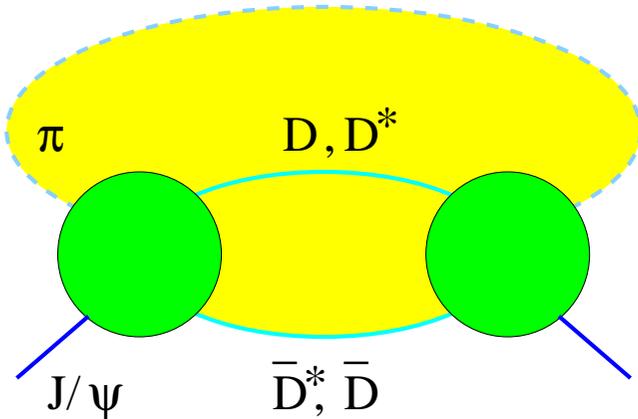
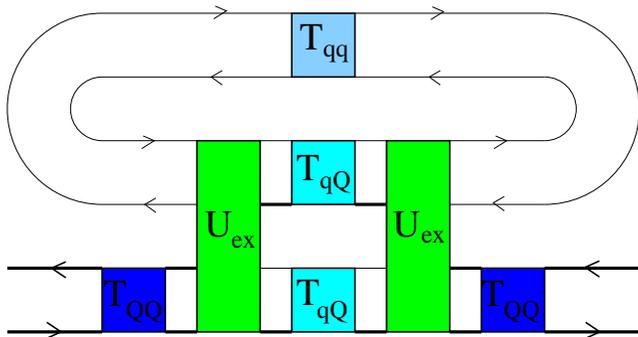


**C. Horowitz et al. PRD (1985), D. B. et al. PLB (1985),
G. Röpke et al. PRD (1986)**

**M. Thoma, Quark Matter '05;
[hep-ph/0509154]**

- Strong correlations present: hadronic spectral functions above T_c (lattice QCD)
- Finite width due to rearrangement collisions (higher order correlations)
- Liquid-like pair correlation function (nearest neighbor peak)

QUANTUM KINETIC APPROACH TO J/ψ BREAKUP



$$\tau^{-1}(p) = \Gamma(p) = \Sigma^>(p) \mp \Sigma^<(p)$$

$$\Sigma^{\lessgtr}(p, \omega) = \int_{p'} \int_{p_1} \int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} |\mathcal{M}|^2 G_{\pi}^{\lessgtr}(p') G_{D_1}^{\lessgtr}(p_1) G_{D_2}^{\lessgtr}(p_2)$$

$$G_h^>(p) = [1 \pm f_h(p)] A_h(p) \text{ and } G_h^<(p) = f_h(p) A_h(p)$$

low density approximation for the final states

$$f_D(p) \approx 0 \Rightarrow \Sigma^<(p) \approx 0$$

$$\tau^{-1}(p) = \int_{p'} \int_{p_2} \int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} |\mathcal{M}|^2 f_{\pi}(p') A_{\pi}(p') A_{D_1}(p_1) A_{D_2}(p_2)$$

$$\frac{d\sigma}{dt} = \frac{1}{16\pi} \frac{|\mathcal{M}(s, t)|^2}{\lambda(s, M_{\psi}^2, s')},$$

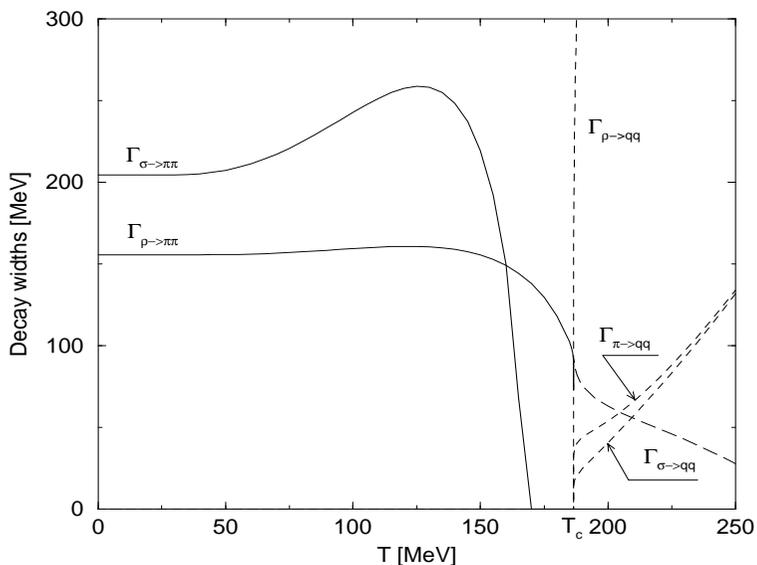
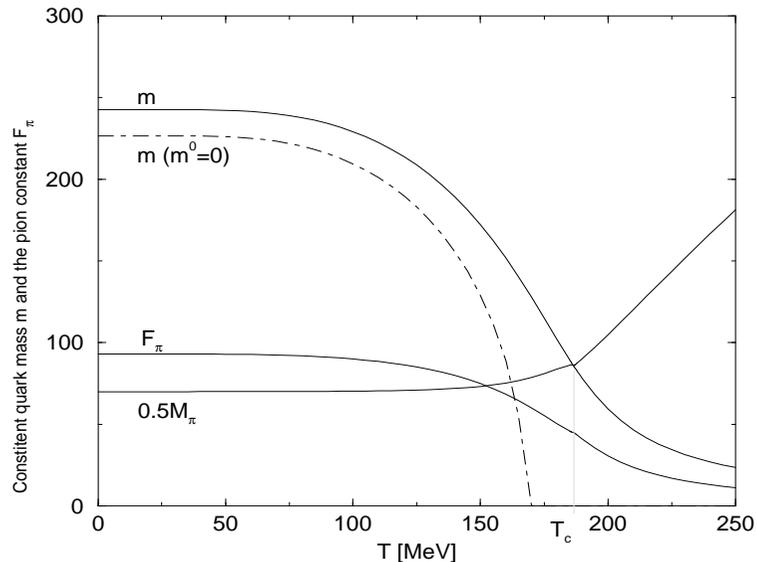
$$\tau^{-1}(p) = \int \frac{d^3\mathbf{p}'}{(2\pi)^3} \int ds' f_{\pi}(\mathbf{p}', s') A_{\pi}(s') v_{\text{rel}} \sigma^*(s)$$

In-medium breakup cross section

$$\sigma^*(s) = \int ds_1 ds_2 A_{D_1}(s_1) A_{D_2}(s_2) \sigma(s; s_1, s_2)$$

Medium effects in **spectral functions** A_h and $\sigma(s; s_1, s_2)$

MOTT EFFECT: NJL MODEL PRIMER



Meson propagator: RPA-type resummation,

$$D_h(P) \sim [1 - G\Pi_h(P)]^{-1},$$

e.g. Pion Pseudoscalar polarization function ($m_q = m_{\bar{q}} = m$)

$$\Pi_\pi(\vec{M}_\pi, \vec{0}) = -\frac{N_c}{8\pi^2} \left\{ 2A(m) - (M_\pi - i\Gamma_\pi/2)^2 B(M_\pi, \vec{0}; m, m) \right\}$$

Finite temperature (Matsubara)

$$A(m) = -4 \int_\Lambda dp \frac{p^2}{\sqrt{E(p)}} \tanh(E(p)/2T) \quad \text{real}$$

$$B(P_0, \vec{0}; m, m) = 8 \int_\Lambda dp \frac{p^2 \tanh(E(p)/2T)}{E(p)[4E^2(p) - P_0^2]} \quad \text{real for } T < T_c$$

Complex polarization function

⇒ Breit-Wigner type **spectral function**

⇐ Blaschke, Burau, Volkov, Yudichev: EPJA 11 (2001) 319

Charm meson sector, see

Gottfried, Klevansky, PLB 286 (1992) 221

Blaschke, Burau, Kalinovsky, Yudichev,
Prog. Theor. Phys. Suppl. 149 (2003) 182

MOTT EFFECT: HEAVY MESON GENERALIZATION

$$\Pi_D(P^2; T) = 4I_1^\Lambda(m_u; T) + 4I_1^\Lambda(m_c; T) + 4 \left(P^2 - (m_u - m_c)^2 \right) I_2^{(\lambda_P, \Lambda)}(P^2, m_u, m_c; T),$$

$$I_2^{(\lambda_M, \Lambda)}(M, m_u, m_c; T) = \frac{N_c}{8\pi^2 M} \int_{\lambda_P}^{\Lambda} dp p^2 \left[\frac{\tilde{E}_{uc} \tanh(E_u/2T)}{E_u(E_u^2 - \tilde{E}_{uc}^2)} + \frac{\tilde{E}_{cu} \tanh(E_c/2T)}{E_c(E_c^2 - \tilde{E}_{cu}^2)} \right],$$

$$\tilde{E}_{ij} = (m_i^2 - m_j^2 + M^2)/2M,$$

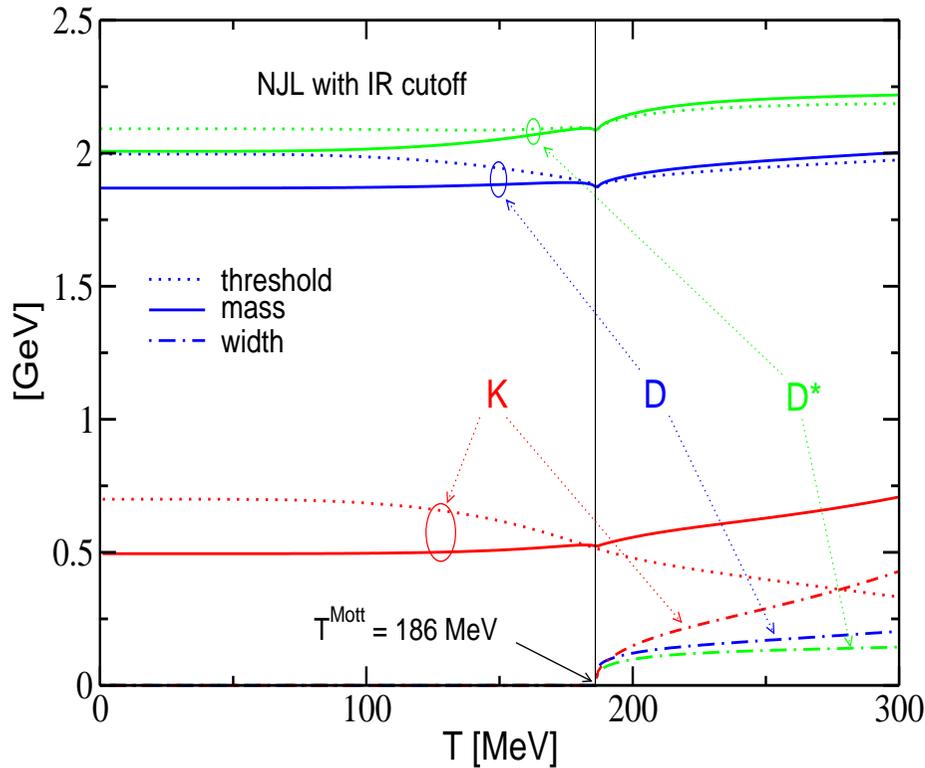
Infrared cutoff ($M_\pi(T_c) = 2m_u(T_c) = 2m_u^{\text{cr}}$)

$$\lambda_P = [m_u^{\text{cr}} \theta(m_u - m_u^{\text{cr}}) + m_u \theta(m_u^{\text{cr}} - m_u)] \times \theta(P^2 - 4(m_u^{\text{cr}})^2) \sqrt{P^2 / (2m_u^{\text{cr}})^2 - 1},$$

Meson spectral properties (mass M , width Γ)

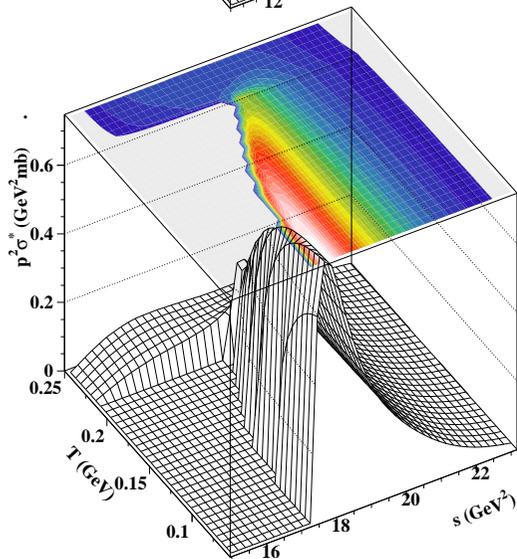
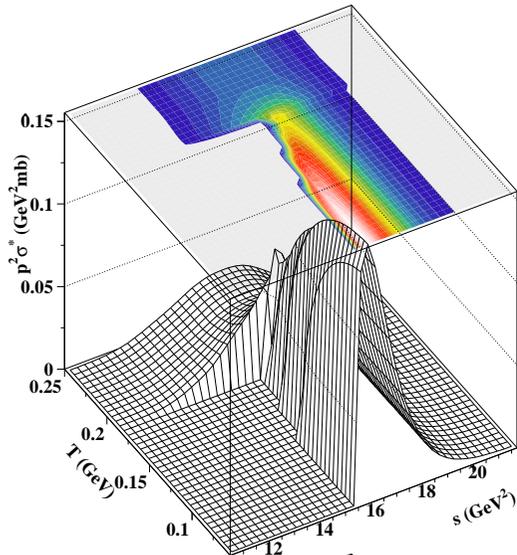
$$G \operatorname{Re}\Pi(P^2 = M^2; T) = 1$$

$$\Gamma(T) = \operatorname{Im}\Pi(M^2; T) / [M(T) \operatorname{Re}\Pi'(M^2; T)]$$



← Blaschke, Burau, Kalinovsky, Yudichev, Prog. Theor. Phys. Suppl. **149** (2003) 182.

IN-MEDIUM J/ψ BREAKUP BY π AND ρ IMPACT



Approximation: $\sigma(s; s_1, s_2) \approx \sigma^{\text{vac}}(s; s_1, s_2)$

Variety of models exists for $\sigma^{\text{vac}}(s; s_1, s_2)$, use a relativistic one
 Blaschke, et al. Heavy Ion Phys. **18** (2003) 49;
 Ivanov, et al. PRD **70** (2004) 014005
 Spectral function for D-mesons as Breit-Wigner

$$A_h(s) = \frac{1}{\pi} \frac{\Gamma_h(T) M_h(T)}{(s - M_h^2(T))^2 + \Gamma_h^2(T) M_h^2(T)} \longrightarrow \delta(s - M_h^2)$$

resonance \leftarrow Mott-effect \leftarrow bound state

See NJL model calculations at finite temperature,

Blaschke et al.: Eur. Phys. J. **A11** (2001) 319

Hüfner et al.: Nucl. Phys. **A606** (1996) 260

Blaschke et al.: Nucl. Phys. **A592** (1995) 561

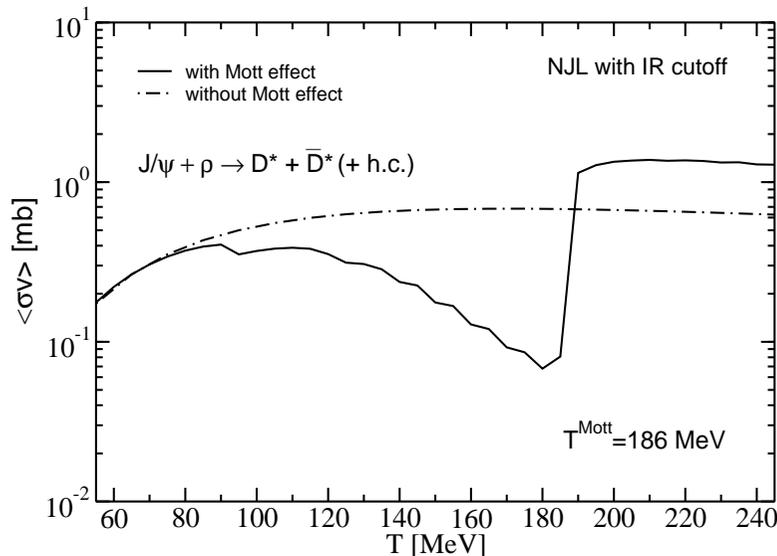
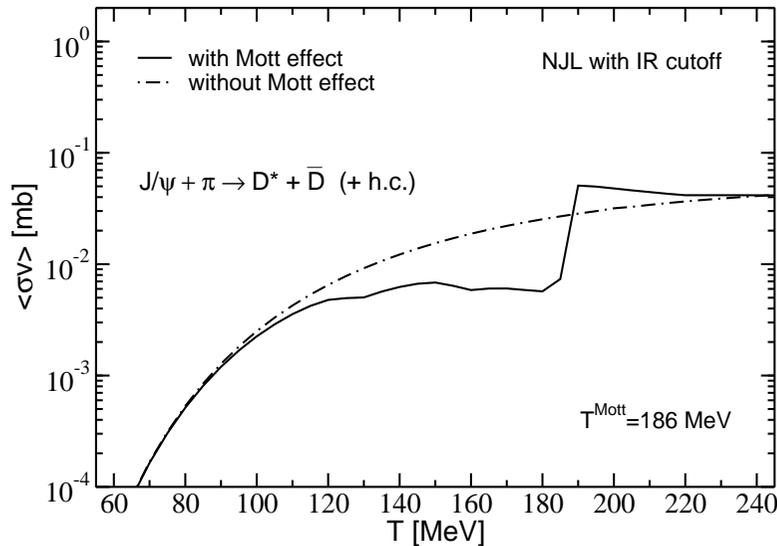
Behaviour above the Mott temperature ($T \sim T_h^{\text{Mott}}$)

$$\Gamma_h(T) \sim (T - T_h^{\text{Mott}})^{1/2} \Theta(T - T_h^{\text{Mott}}),$$

$$M_h(T) = M_h(T_h^{\text{Mott}}) + 0.5 \Gamma_h(T)$$

NJL model with IR cutoff: $T_h^{\text{Mott}} = 186 \text{ MeV}$ universal

J/ψ DISSOCIATION RATE IN A π/ρ RESONANCE GAS



Dissociation rate for a J/ψ at rest in a hot resonance gas
($h = \pi, \rho$)

$$\tau^{-1}(T) = \tau_{\pi}^{-1}(T) + \tau_{\rho}^{-1}(T)$$

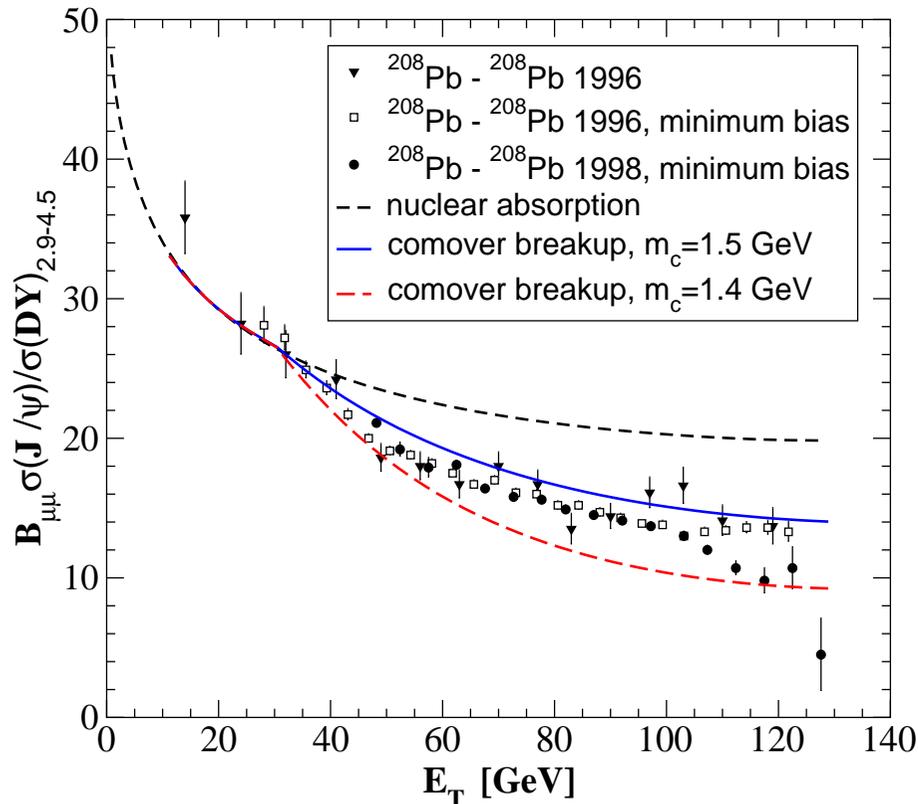
$$\begin{aligned} \tau_h^{-1}(T) &= \int \frac{d^3p}{(2\pi)^3} \int ds' A_h(s'; T) f_h(p, s'; T) j_h(p, s') \sigma_h^*(s; T) \\ &= \langle \sigma_h^* v_{\text{rel}} \rangle n_h(T), \end{aligned}$$

$$f_h(p, s; T) = g_h \{ \exp[(\sqrt{p^2 + s} - \mu)/T] - 1 \}^{-1}$$

$$s(p, s') = s' + M_{\psi}^2 + 2M_{\psi} \sqrt{p^2 + s'}$$

- Masses slightly rising below T^{Mott}
⇒ reduction of breakup rate
- Mott-effect for intermediate states at T^{Mott}
⇒ breakup enhancement - “subthreshold” process
- Structure in the breakup rate at $T = T^{\text{Mott}}$
- Additional J/ψ absorption channel opens
⇒ “anomalous” suppression

TOWARDS AN INTERPRETATION OF “ANOMALOUS” J/ψ SUPPRESSION



Blaschke, Burau, Kalinovsky, Proc. HQP-5,
Dubna (2000); [nucl-th/0006071]

More detailed description: additional resonances, gain processes (D-fusion), HIC simulation

Grandchamp et al., PL B523 (2001); NP A709 (2002) 415; PRL 92 (2004) 212301; J. Phys. G 30 (2004) S1355.

Modified Glauber model calculation

Wong, PRL76 (1996) 196;

Martins, Blaschke, Proc. HQP-4; [hep-ph/9802250]

$$S(E_T) = S_N(E_T) \exp \left[- \int_{t_0}^{t_f} dt \tau^{-1}(n(t)) \right]$$

$$= S_N(E_T) \exp \left[\int_{n_0(E_T)}^{n_f} dn \langle \sigma^* v_{\text{rel}} \rangle \right]$$

Nucl. abs: $S_N(E_T) = 18 + 36 \exp(-0.26\sqrt{E_T})$

Longitudinal expansion: $n(t) = n_0(E_T)t_0/t$

Impact parameter representation of $n_0(E_T)$:

$$E_T(b)/\text{MeV} = 130 - b/\text{fm}$$

$$n_0(b)/\text{fm}^{-3} = 1.2\sqrt{1 - (b/10.8 \text{ fm})^2}.$$

Threshold: Mott effect for D-Mesons

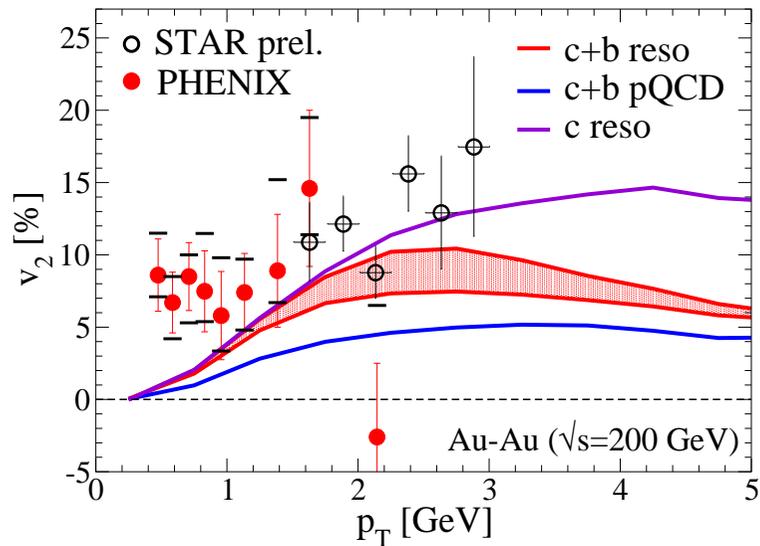
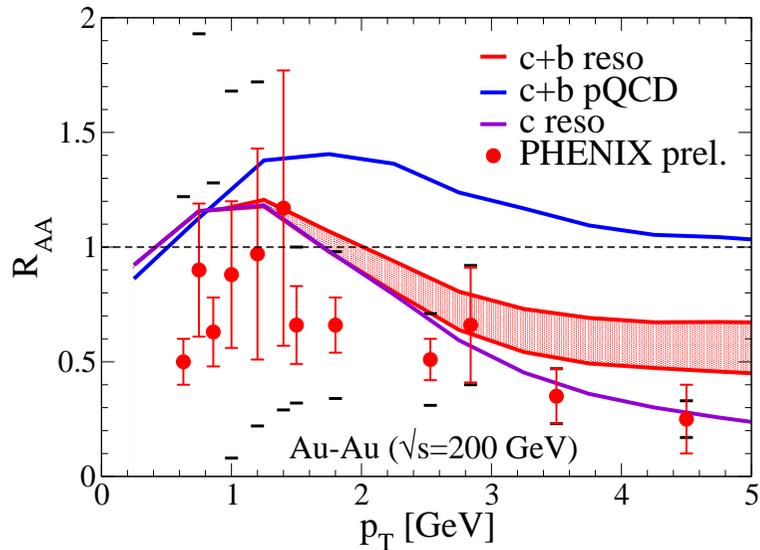
CONCLUSIONS

- **Mott effect** is a universal feature in dense hadronic matter
- Hadronic resonances above T_c and T_{Mott} can be described within T-matrix approach
- Rearrangement collisions of (off-shell) resonances within the Kadanoff/Baym - Schwinger/Keldysh formalism
- Anomalous J/ψ suppression due to Mott effect for D-mesons (breakup channel opens)

OUTLOOK

- Inputs from Lattice (Potentials) need clarification
- Recalculate breakup cross sections with consistent inputs
- Solution of the full kinetic equation with gain process
- Evaluate pair correlation function and relation to hydrodynamics of the s-QGP

CHARM PRODUCTION: OUTLOOK

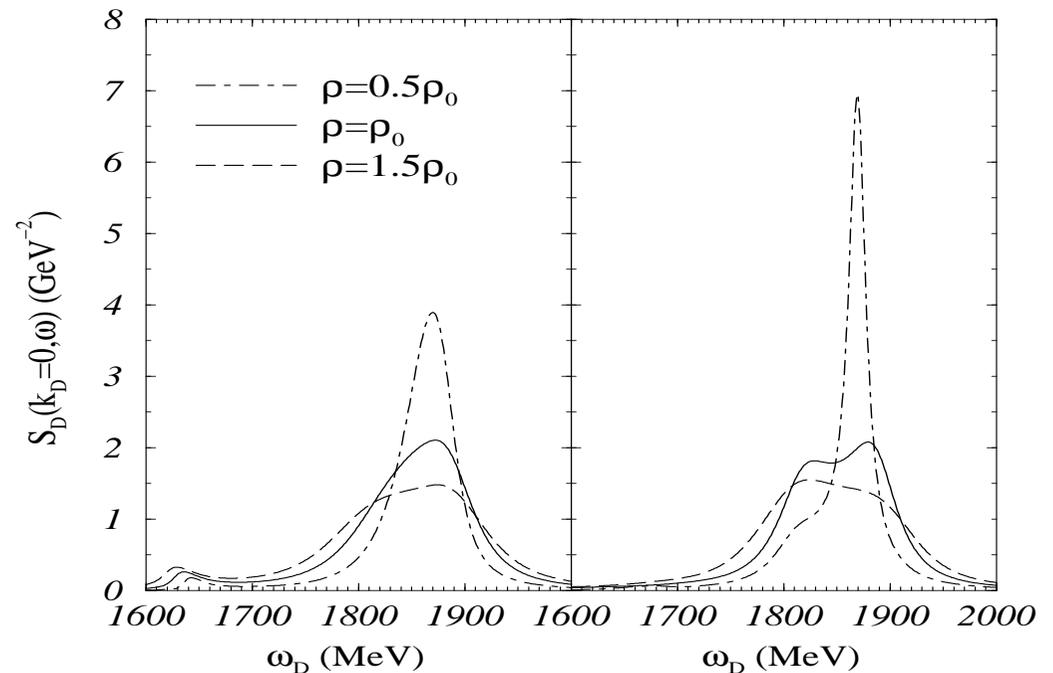


Hees, Greco, Rapp, nucl-th/0508055

Nuclear modification factor R_{AA} and elliptic flow v_2 of semileptonic D^- and B^- meson decay-electrons in $b = 7$ fm Au-Au ($\sqrt{s} = 200$ GeV) collisions at RHIC

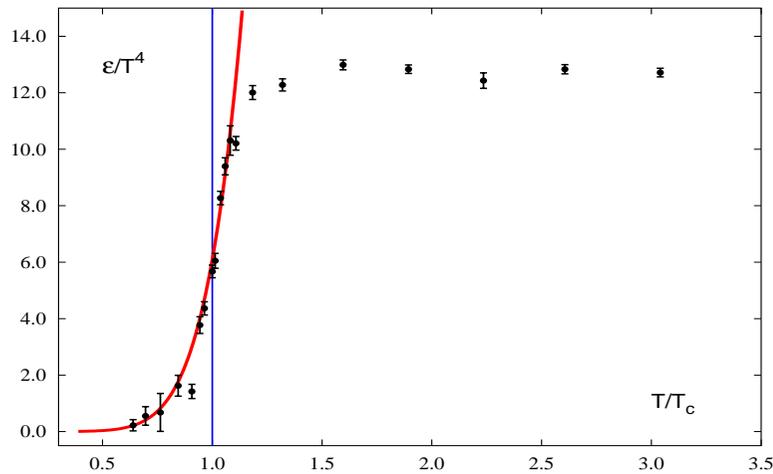
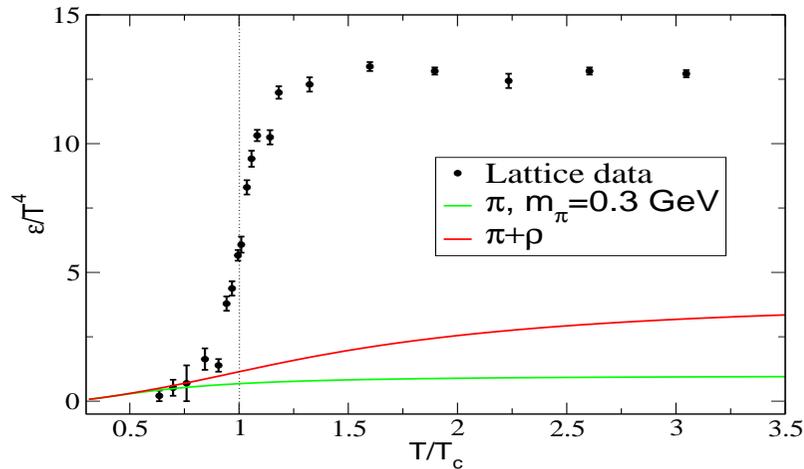


D-meson spectral function in cold dense nuclear matter from a G-matrix approach ↓



Tolos et al., EPJC (2005); nucl-th/0501151

LATTICE QCD EoS VS. RESONANCE GAS



Ideal hadron gas mixture ...

$$\varepsilon(T) = \sum_{i=\pi,\rho,\dots} g_i \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2 + m_i^2}}{\exp(\sqrt{p^2 + m_i^2}/T) + \delta_i}$$

missing degrees of freedom below and above T_c

Resonance gas ... [Karsch et al., hep-ph/0303108](#)

$$\varepsilon(T) = \sum_{i=\pi,\rho,\dots} \varepsilon_i(T) + \sum_{r=M,B} g_r \int dm \rho(m) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2 + m^2}}{\exp(\sqrt{p^2 + m^2}/T) + \delta_r}$$

$\rho(m) \sim m^\beta \exp(m/T_H)$... Hagedorn Massenspektrum

too many degrees of freedom above T_c

LATTICE QCD EoS AND MOTT-HAGEDORN GAS

$$\varepsilon(T, \{\mu_j\}) = \sum_{i=\pi, K, \dots} \varepsilon_i(T, \{\mu_i\}) + \sum_{r=M, B} g_r \int_{m_r} dm \int ds \rho(m) A(s, m; T) \int \frac{d^3 p}{(2\pi)^3} \frac{\sqrt{p^2 + s}}{\exp\left(\frac{\sqrt{p^2 + s} - \mu_r}{T}\right) + \delta_r}$$

Hagedorn mass spectrum: $\rho(m)$

Spectral function for heavy resonances:

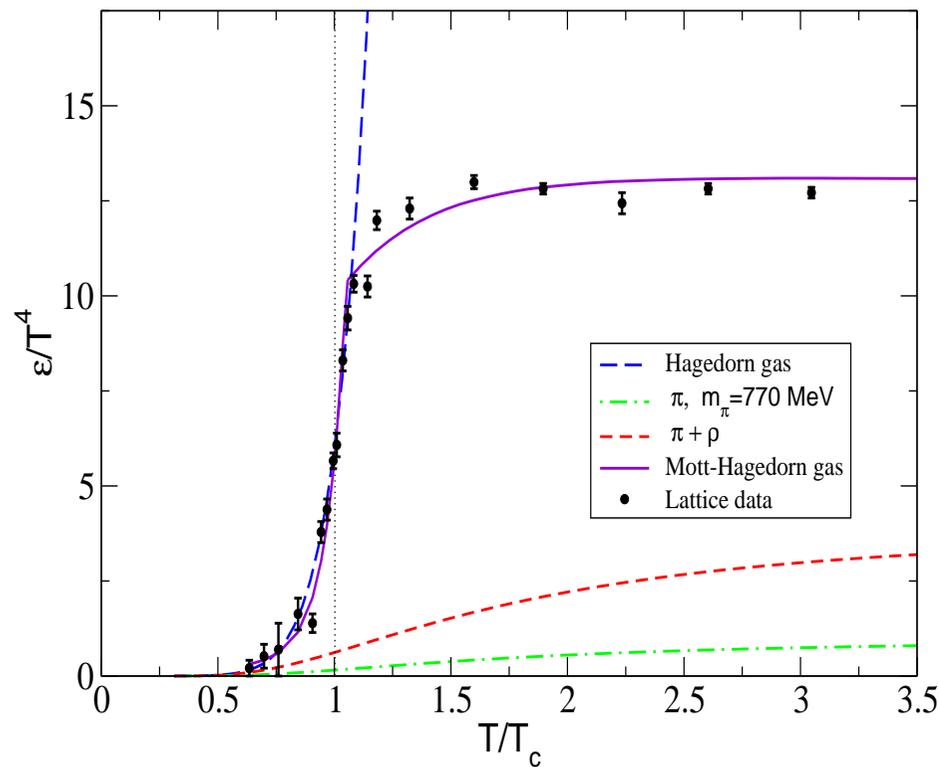
$$A(s, m; T) = N_s \frac{m \Gamma(T)}{(s - m^2)^2 + m^2 \Gamma^2(T)}$$

Ansatz with **Mott effect** at $T = T_c = 165$ MeV:

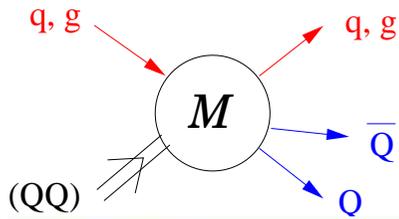
$$\Gamma(T) = B \Theta(T - T_c) \left(\frac{m}{T_c}\right)^4 \left(\frac{T}{T_c}\right)^{2.55} \exp\left(\frac{m}{T_c}\right)$$

No width below T_c : statistical Bootstrap model

Blaschke & Bugaev, Fizika B13, 491 (2004)
Prog. Part. Nucl. Phys. 53, 197 (2004)



HOT, DENSE QUARK GLUON PLASMA: QUANTUM KINETIC EFFECTS



LOSS process

$$\Sigma^>(p) = \int_{p'} \int_{p_1} \dots \int_{p_3} (2\pi)^4 \delta_{p+p', p_1+p_2+p_3} |\mathcal{M}|^2 f(p') A(p') A(p_1) A(p_2) A(p_3) [1 \pm f_1(p_1)][1 - f_Q(p_2)][1 - f_{\bar{Q}}(p_3)]$$

quark (gluon) Impact \Rightarrow Pauli-Blocking (Bose-Enhancement)

GAIN process

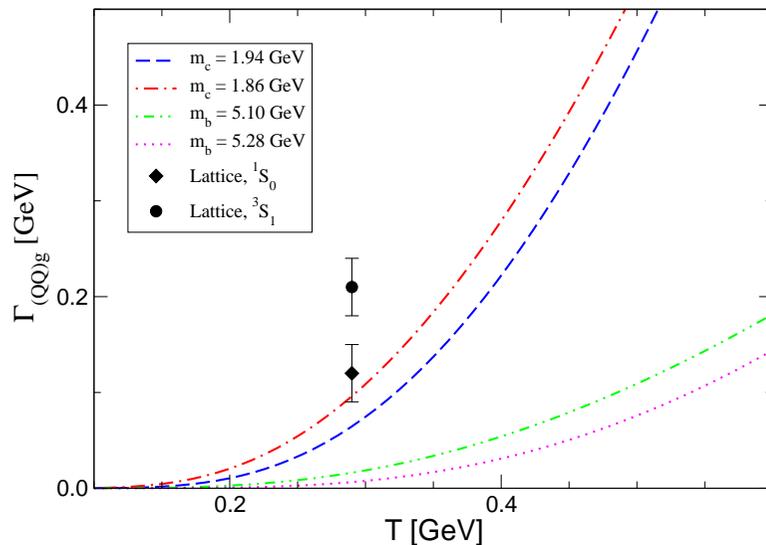
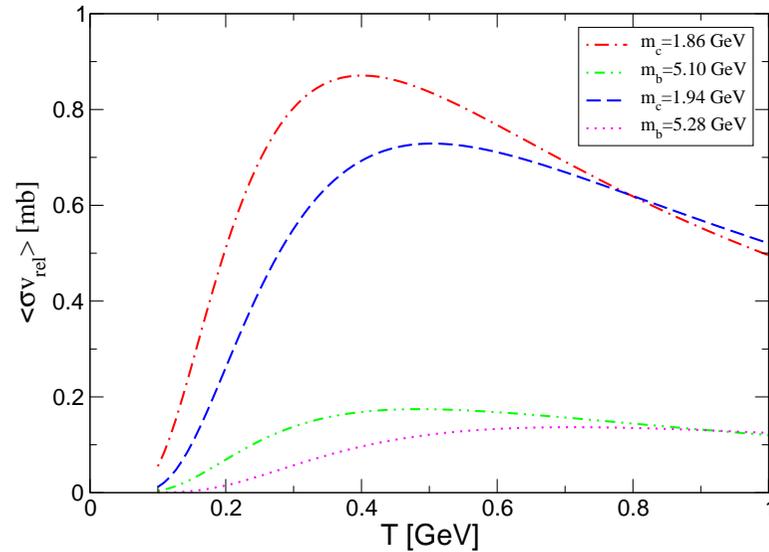
$$\Sigma^<(p) = \int_{p'} \int_{p_1} \dots \int_{p_3} (2\pi)^4 \delta_{p+p', p_1+p_2+p_3} |\mathcal{M}|^2 [1 \pm f(p')] A(p') f_1(p_1) f_Q(p_2) f_{\bar{Q}}(p_3) A(p_1) f_Q(p_2) A(p_2) A(p_3)$$

Without Quantum statistical effects:

LOSS (Ionization) $\propto n_q, n_g, (n_h)$

GAIN (Recombination) $\propto n_Q, n_{\bar{Q}}, (n_1)$

QUARKONIUM DISSOCIATION RATE IN GLUON GAS



CERN Yellow Report (2003), hep-ph/0311048

Quarkonium breakup cross section by gluon impact
Bhanot, Peskin, NP B 156 (1979) 391

$$\sigma_{(Q\bar{Q})g} = \frac{2^{11}}{3^4} \alpha_s \pi a_0^2 \frac{(\omega/\epsilon_0 - 1)^{3/2}}{(\omega/\epsilon_0 - 1)^5} \Theta(\omega - \epsilon_0)$$

Coulombic 1S quarkonium bound state with rms radius

$$\sqrt{\langle r^2 \rangle}_{1S} = \sqrt{3} a_0 = 2\sqrt{3}/(\alpha_s m_Q)$$

Values for binding energy and heavy quark mass

Arleo, et al. , PR D 65 (2002) 014005

System	ϵ_0 [GeV]	m_Q [GeV]	ϵ_0 [GeV]	m_Q [GeV]
bottomonium	0.75	5.10	1.10	5.28
charmonium	0.78	1.94	0.62	1.68

Dissociation rate for a J/ψ at rest in a hot gluon gas

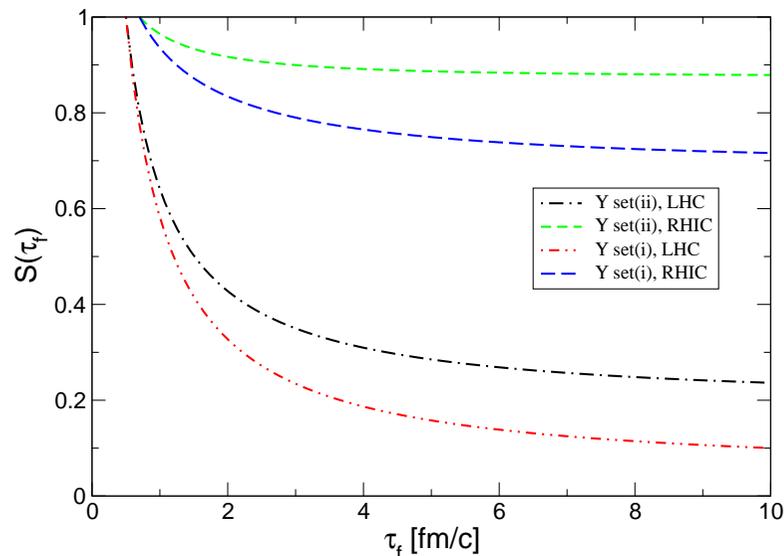
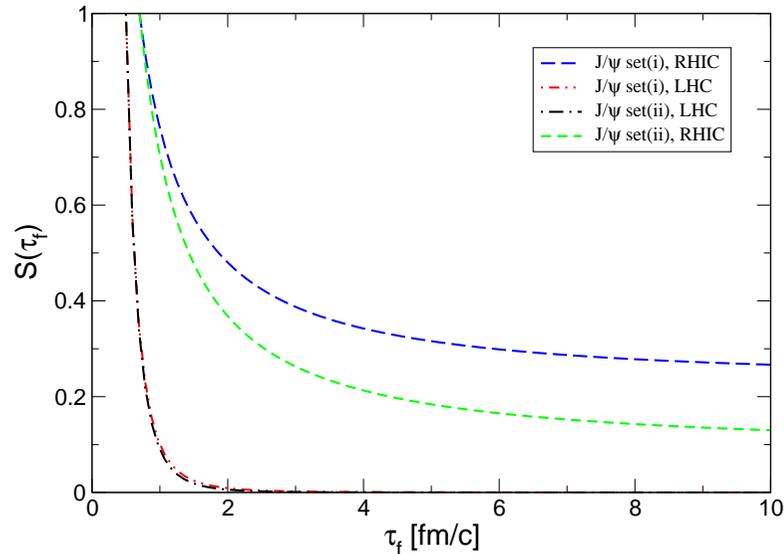
$$\tau_{(Q\bar{Q})g}^{-1}(T) \equiv \Gamma_{(Q\bar{Q})g}(T) = \langle \sigma_{(Q\bar{Q})g}(\omega) n_g(\omega) \rangle_T$$

Thermal gluon distribution

$$n_g(\omega) = g_g \{ \exp[\omega_g(p)/T] - 1 \}^{-1}, \quad g_g = 2(N_c^2 - 1) = 16$$

Lattice: Umeda et al [hep-lat/0211003]

HEAVY QUARKONIA DISSOCIATION IN A GLUON GAS



Bjorken scenario: $T^3 t = T_0^3 t_0 = \text{const}$

Quarkonium survival probability
neglecting nucleon absorption, hadronic comovers (resonances) and hadronization effects:

$$S(t_f) = \exp\left(-\int_{t_0}^{t_f} dt \tau_{(Q\bar{Q})g}^{-1}(T)\right)$$

Initial conditions for Plasma evolution
(Xu et al. PR C53 (1996) 3051)

	LHC	RHIC	SPS
$T_0[\text{GeV}]$	0.72	0.4	0.25
$\tau_0[\text{fm}/c]$	0.5	0.7	1.0

Results for LHC conditions:

- J/ψ 's will not survive passage through plasma
 $\Rightarrow p_T$ dependence provides more complete picture
- Υ can be a good probe of plasma lifetime/ temperature

Secondary production, quark impact and medium effects can modify the picture quantitatively.